<u>CLAIMS</u>

1. A ceramic matrix composite tubular shell structure having an inner wall, an outer wall and a plurality of cooling channels formed between said inner wall and said outer wall wherein said ceramic matrix composite tubular shell structure comprises:

a. a fibrous preform of refractory fibers;

b. a fiber coating which fully encapsulates the refractory fibers of said fibrous preform; and

c. a ceramic matrix material which fully encapsulates and consolidates the coated fibers of the said fibrous preform into a densified composite material.

2. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein the refractory fibers of said fibrous preform are selected from a group comprising continuous and discontinuous high-temperature fibers.

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3. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein the refractory fibers of said fibrous preform are selected from a group comprising carbon, silicon carbide, aluminum oxide, and other fibers capable of withstanding temperatures in excess of 800°C.

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Method

4. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said fibrous preform is produced by a textile fabrication process selected from a group of fabrication processes comprising weaving, braiding, knitting, filament winding, felting, and needling.

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5. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said fiber coating is a material having a thickness of 0.05-5.0 micrometers and is selected from a group of materials comprising carbon, silicon carbide, boron carbide, tantalum

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carbide, hafnium carbide, zirconium carbide, silicon nitride, boron nitride, tantalum nitride, hafnium nitride, zirconium nitride, titanium nitride, aluminum nitride, silicon boride, tantalum boride, hafnium boride, zirconium boride, titanium boride, zirconium silicide, titanium silicide, molybdenum silicide, aluminum oxide, silicon oxide, boron oxide, tantalum oxide, hafnium oxide, zirconium oxide, and titanium oxide.

6. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said fiber coating comprises a single-layer phase of uniform material composition.

7. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said fiber coating comprises a multilayered phase including two or more alternating coating layers having two or more fiber coating material compositions.

8. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said fiber coating comprises a single-layer phase of mixed material composition.

9. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said ceramic matrix material is selected from a group of materials comprising carbon, silicon carbide, boron carbide, tantalum carbide, hafnium carbide, zirconium carbide, silicon nitride, boron nitride, tantalum nitride, hafnium nitride, zirconium nitride, titanium nitride, aluminum nitride, silicon boride, tantalum boride, hafnium boride, zirconium boride, titanium boride, zirconium silicide, titanium silicide, molybdenum silicide, aluminum oxide, silicon oxide, boron oxide, tantalum oxide, hafnium oxide, zirconium oxide, and titanium oxide.

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10. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said ceramic matrix material comprises a single phase of uniform material composition.

11. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said ceramic matrix material comprises a multilayered phase including two or more alternating matrix layers having two or more ceramic matrix material compositions.

12. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said ceramic matrix material comprises a single phase of mixed material composition.

13. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said tubular shell structure has a tubular geometry with said plurality of cooling channels annularly arranged around and formed between said inner wall and said outer wall thereof.

14. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said tubular shell structure is a cylindrical heat exchanger tube with said plurality of cooling channels having a corresponding cylindrical profile and formed between said inner wall and said outer wall of said heat exchanger tube.

15. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said tubular shell structure comprises a rocket propulsion thrust chamber having a converging-diverging geometric profile with said plurality of cooling channels having a corresponding converging-diverging geometric profile and formed between said inner wall and said outer wall of said rocket propulsion thrust chamber.

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16. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said tubular shell structure has a longitudinal axis, and said plurality of cooling channels formed between said inner wall and said outer wall thereof are oriented axially with respect to the longitudinal axis of said tubular shell structure.

17. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said tubular shell structure has a longitudinal axis, and said plurality of cooling channels formed between said inner wall and said outer wall thereof are oriented helically with respect to the longitudinal axis of said tubular shell structure.

18. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said tubular shell structure has a longitudinal axis, and said plurality of cooling channels formed between said inner wall and said outer wall thereof are oriented in parallel alignment and undulate sinusoidally with respect to the longitudinal axis of said tubular shell structure.

19. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said plurality of cooling channels are located in an annular array between said inner wall and said outer wall of said tubular shell structure with each cooling channel of said plurality thereof having a trapezoidal-shaped cross-sectional geometry.

20. The ceramic matrix composite tubular shell structure recited in claim **19**, wherein said plurality of cooling channels are nested in an annular assemblage between said inner wall and said outer wall to form said annular array thereof, said annular array of cooling channels located in intimate contact with said inner wall and said outer wall of said tubular shell structure.

21. The ceramic matrix composite tubular shell structure recited in claim **1**, wherein said plurality of cooling channels form a corresponding plurality of radial webs by which to mechanically couple said inner wall and said outer wall of said tubular shell into a high-efficiency unitized monocoque structure.

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22. A method for manufacturing a ceramic matrix composite tubular shell structure having an inner wall, an outer wall and a plurality of cooling channel passages formed between said inner wall and said outer wall, wherein said ceramic matrix composite tubular shell structure is manufactured by the steps comprising:

a. fabricating an inner tooling mandrel for defining the inside geometry of said inner wall;

b. fabricating a plurality of cooling channel tooling mandrel segments for defining the inside geometry of said plurality of cooling channel passages of said tubular shell structure;

c. fabricating a fibrous preform of refractory reinforcing fibers;

d. depositing a fiber coating onto said fibrous preform which fully encapsulates the refractory reinforcing fibers thereof;

e. depositing a ceramic matrix material onto said fibrous preform to fully encapsulate and consolidate said coated fibrous preform into a densified fiber reinforced ceramic matrix composite material;

f. removing said inner tooling mandrel and said plurality of cooling channel tooling mandrel segments from said densified ceramic matrix composite tubular shell structure;

g. machining said densified ceramic matrix composite tubular shell structure; and

h. depositing a ceramic seal coating material onto said densified ceramic matrix composite tubular shell structure following said machining of said tubular shell structure.

23. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein the said inner tooling mandrel and said plurality of cooling channel tooling mandrel segments are fabricated from a material selected from a group of materials comprising graphite, molybdenum and steel.

24. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein said inner tooling mandrel has a geometric profile.

25. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **24**, wherein said ceramic matrix composite tubular shell structure comprises an actively-cooled heat exchanger tube having a cylindrical shape and said inner tooling mandrel has a corresponding cylindrical geometric profile.

26. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **24**, wherein said ceramic matrix composite tubular shell structure comprises an actively-cooled rocket propulsion thrust chamber having a converging-diverging shape and said inner tooling mandrel has a corresponding converging-diverging geometric profile.

27. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **26**, wherein said inner tooling mandrel having said converging-diverging geometric profile comprises a 2-piece assembly which is split at the location of minimum diameter and secured by a bolted fastener.

28. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein said plurality of cooling channel tooling mandrel segments are fabricated by the steps comprising:

a. forming a base tubular tooling mandrel having generally independent inner and outer geometric profiles corresponding to the cross-sectional dimensions of the plurality of cooling passages; and

b. sectioning said base tubular tooling mandrel at periodic angular intervals to produce said plurality of cooling channel tooling mandrel segments.

29. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **28**, wherein the inner geometric profile of said base tubular tooling mandrel conforms to the geometric profile of said inner tooling mandrel and incorporates a radial gap to accommodate the thickness of said fibrous preform.

30. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **28**, wherein said plurality of cooling channel tooling mandrel segments are fabricated by the additional step of cutting said base tubular tooling mandrel at periodic intervals with a kerf width corresponding to the thickness of said fibrous preform of refractory reinforcing fibers.

31. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **28**, wherein the step of sectioning said base tubular tooling mandrel includes the additional step of cutting said base tubular tooling mandrel at periodic intervals to produce a plurality of like axially extending cooling channel tooling mandrel segments.

32. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **28**, wherein the step of sectioning said base tubular tooling mandrel includes the additional step of cutting said base tubular tooling mandrel at periodic intervals to produce a plurality of like helically spiraling cooling channel tooling mandrel segments.

33. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **28**, wherein the step of sectioning said base tubular tooling mandrel includes the additional step of cutting said base tubular tooling mandrel at periodic intervals to produce a plurality of like sinusoidally undulating cooling channel tooling mandrel segments.

34. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein said fibrous preform is fabricated from an assemblage of individual fiber preform elements produced by a textile fabrication process selected from a group of fabrication processes comprising weaving, braiding, knitting, fiber placement, filament winding, felting, and needling.

35. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, comprising the additional step of forming an inner wall fiber preform element onto said inner tooling mandrel, wherein said inner wall fiber preform element is produced by a textile fabrication process selected from a group of fabrication processes comprising weaving, braiding, knitting, fiber placement, filament winding, felting, and needling.

36. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, comprising the additional step of forming a plurality of cooling channel fiber preform elements onto repective ones of said plurality of cooling channel tooling mandrel segments, wherein said plurality of cooling channel fiber preform elements are produced by a textile fabrication process selected from a group of fabrication processes comprising weaving, braiding, knitting, fiber placement, filament winding, felting, and needling.

37. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **36**, wherein said plurality of cooling channel fiber preform elements are disposed around said inner wall fiber preform element in an annular array.

38. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **37**, wherein said plurality of cooling channel fiber preform elements disposed around said inner wall fiber preform element in an annular array are compacted firmly against said inner wall fiber preform element and secured by a tight wrapping of tape to thereby form a fibrous preform sub-assembly.

39. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, comprising the additional step of forming an outer wall fiber preform element onto said fibrous preform sub-assembly to fabricate said fibrous preform, wherein said outer wall fiber preform element is produced by a textile fabrication process selected from a group of fabrication processes comprising weaving, braiding, knitting, fiber placement, filament winding, felting, and needling.

40. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein the fiber coating deposited on said fibrous preform has a thickness of 0.05-5.0 micrometers and is produced by a process selected from a group of fiber coating processes comprising chemical vapor infiltration (CVI), polymer precursor impregnation/pyrolysis (PIP), reaction formation, and combinations thereof.

41. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **40**, wherein the fiber coating deposited on said fibrous preform is carbon produced by chemical vapor infiltration using a carbon-forming precursor selected from a group of chemical precursors comprising methane, propane, propylene, and mixtures

thereof, which is pyrolytically decomposed into carbon at an elevated temperature of 950-1250°C and at a reduced pressure of 1-250 Torr.

42. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **40**, wherein the fiber coating deposited on said fibrous preform is boron nitride produced by chemical vapor infiltration using a boron nitride-forming precursor selected from a group of chemical precursors comprising boron trichloride, boron triflouride, diborane, and mixtures thereof, which is reduced with a reductant selected from a group of chemical reductants comprising nitrogen, hydrogen, ammonia, and mixtures thereof to form boron nitride at an elevated temperature of 700-1200°C and at a reduced pressure of 1-250 Torr.

43. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **40**, wherein said fibrous preform is first coated with carbon followed by a boron carbide coating produced by chemical vapor infiltration using a boron carbide-forming precursor selected from a group of chemical precursors comprising boron trichloride, boron triflouride, diborane, and mixtures thereof, which is reacted with a carbon-forming precursor selected from a group of chemical reactants comprising methane, propane, propylene, and mixtures thereof to form boron carbide at an elevated temperature of 800-1100°C and at a reduced pressure of 1-250 Torr.

44. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein said fiber coated fibrous preform is consolidated with a ceramic matrix material produced by a process selected from a group of matrix consolidation processes comprising chemical vapor infiltration (CVI), polymer precursor impregnation/pyrolysis (PIP), melt infiltration (MI), reaction formation, and

combinations thereof, which fully encapsulates said coated reinforcing fibers of said fibrous preform for transforming said fibrous preform into a dense, ceramic matrix composite structure.

45. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **44**, wherein said ceramic matrix material is silicon carbide produced by chemical vapor infiltration using a silicon carbide-forming precursor selected from a group of chemical precursors comprising methyltrichlorosilane, dimethyldichlorosilane, silicon tetrachloride with methane, and mixtures thereof, which is reacted to form silicon carbide at an elevated temperature of 850-1150°C and at a reduced pressure of 1-250 Torr.

46. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **44**, wherein said ceramic matrix material is carbon produced by chemical vapor infiltration using a carbon-forming precursor selected from a group of chemical precursors comprising methane, propane, propylene, and mixtures thereof, which is pyrolytically decomposed into carbon at an elevated temperature of 950-1250°C and at a reduced pressure of 1-250 Torr.

47. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **44**, wherein said ceramic matrix material is boron carbide produced by chemical vapor infiltration using a boron carbide-forming precursor selected from a group of chemical precursors comprising boron trichloride, boron triflouride, diborane, and mixtures thereof, which is reacted with a carbon-forming precursor selected from a group of chemical reactants comprising methane, propane, propylene, and mixtures thereof to form boron carbide at an elevated temperature of 800-1100°C and at a reduced pressure of 1-250 Torr.

48. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein said plurality of cooling channel tooling mandrel segments which define the inside geometry of said plurality of cooling channel passages are destructively removed from said ceramic matrix composite tubular shell structure by a process selected from a group of removal processes comprising acid digestion, oxidation and grit blasting.

49. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **48**, wherein said plurality of cooling channel tooling mandrel segments are fabricated from graphite and are destructively removed from said ceramic matrix composite tubular shell structure by a process selected from a group of removal processes comprising oxidation and grit blasting.

50. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **48**, wherein said plurality of cooling channel tooling mandrel segments are fabricated from metal and are destructively removed from said ceramic matrix composite tubular shell structure by a process including acid digestion.

51. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **22**, wherein said densified fiber reinforced ceramic matrix composite tubular shell structure is seal coated with said ceramic seal coating material following removal of said inner tooling mandrel and said plurality of cooling channel tooling mandrel segments from said ceramic matrix composite tubular shell structure, said ceramic seal coating material produced by a process selected from a group of coating processes comprising chemical vapor infiltration (CVI), polymer precursor impregnation/pyrolysis (PIP), melt infiltration (MI), reaction formation, and combinations thereof.

52. The method for manufacturing a ceramic matrix composite tubular shell structure recited in claim **51**, wherein said densified fiber reinforced ceramic matrix composite tubular shell structure is seal coated with silicon carbide produced by chemical vapor infiltration using a silicon carbide-forming precursor selected from a group of chemical precursors comprising methyltrichlorosilane, dimethyldichlorosilane, silicon tetrachloride and methane, which is reacted to form silicon carbide at an elevated temperature of 850-1150°C and at a reduced pressure of 1-250 Torr.